Development of a MARS superconducting cold mass for future generations of ECRIS

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Lawrence Berkeley National Laboratory

2024 NP Accelerator R&D PI Exchange Meeting

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Acknowledgements

- 88-inch Cyclotron, NS Division, LBNL
  - Brian Bell, Janilee Benitez, Patrick Coleman, Jaime Cruz Duran, Jeff Hansen, Rae de Leon, Jacob Melendrez, Roman Nieto, Larry Phair, Chris Reardon, Nathan Seidman, Damon Todd, Daniel Xie, Lianrong Xu, and Sean Zhong

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Outline

- Introduction: description and goals of the project
- MARS cold mass design
- Project status
- Annual budget
- Project deliverables and schedule

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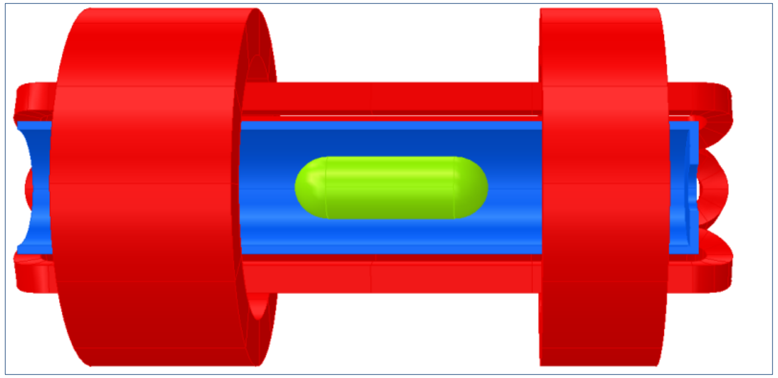
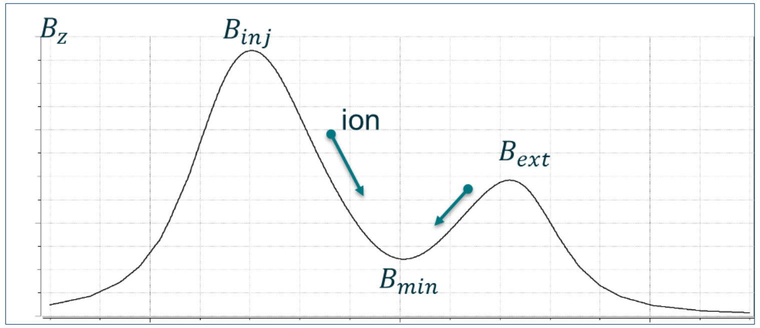
Introduction
ECR Ion Sources

- Produce a plasma from which we extract an ion beam
- Plasma is confined using sextupole and solenoid magnets

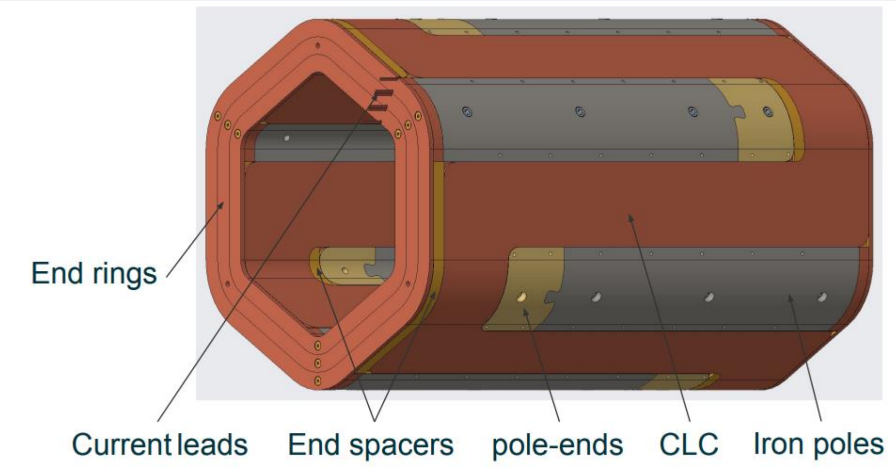


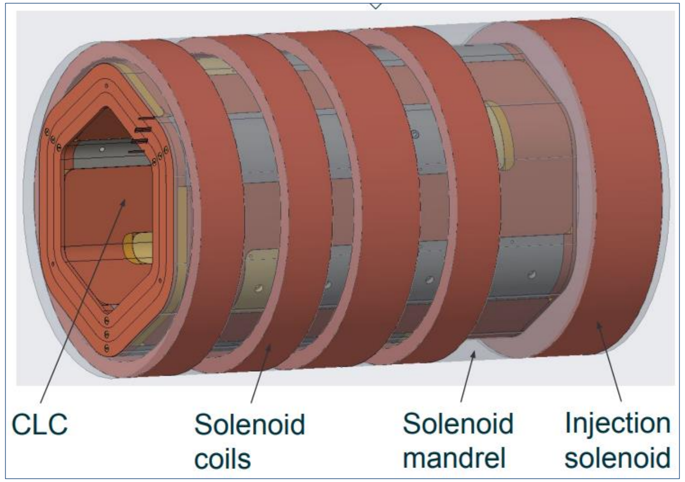
- Currently, 3rd generation sources, like VENUS and FRIB, use superconducting magnets
  - Frequency of 28 GHz
  - Solenoid field up to 4T
  - Sextupole field up to 2 T

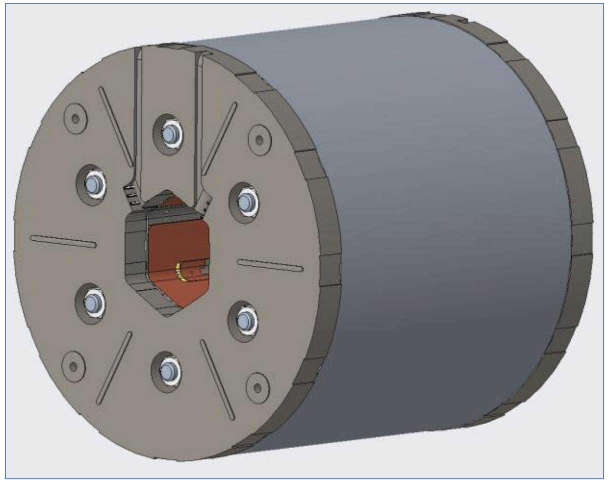


Introduction
Goal of the project

- Design, fabricate, and test the cold mass of the 4th generation ECR Ion Source MARS capable of reaching a magnetic field that satisfies 45 GHz operation
  - Based on a new coil design, never fabricated and tested before







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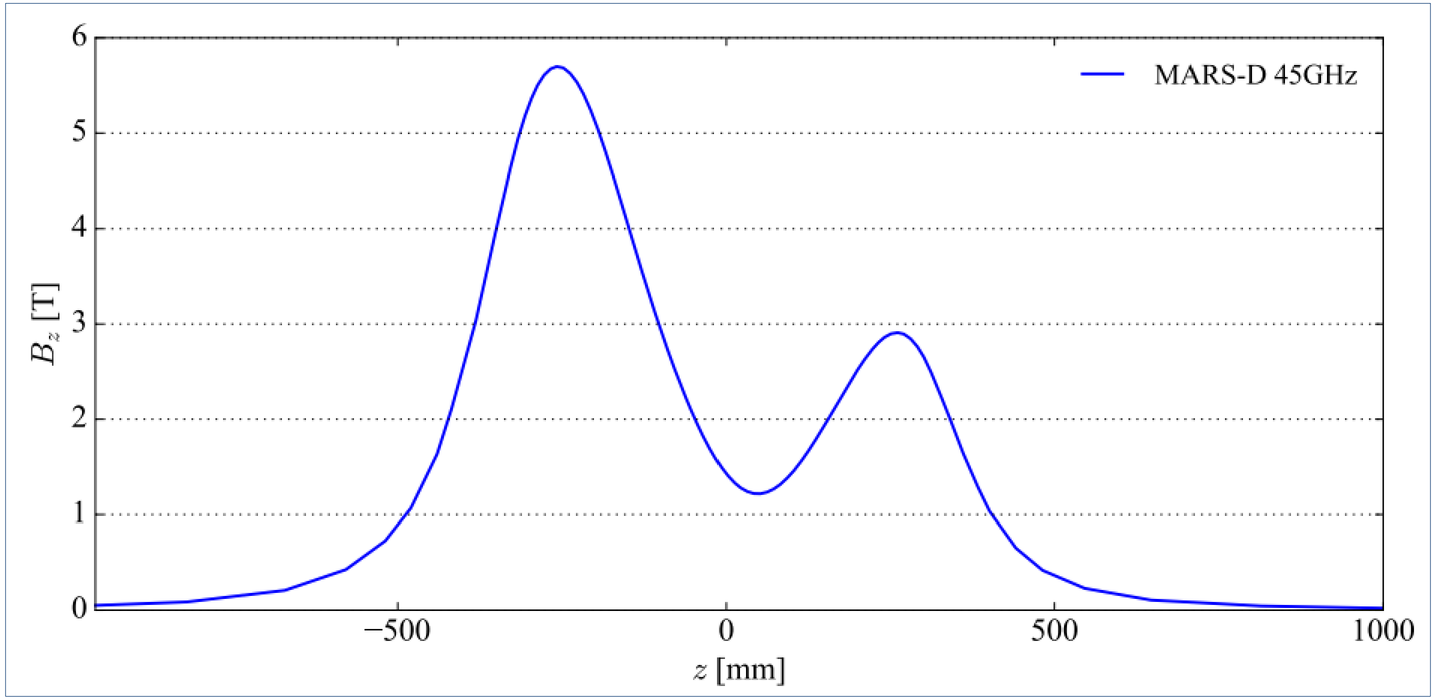
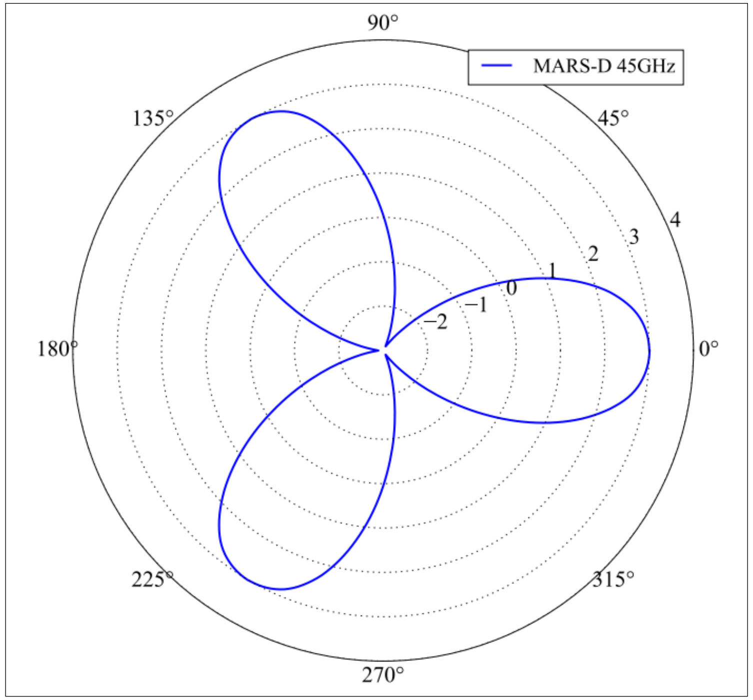
Requirements for a 45 GHz operation

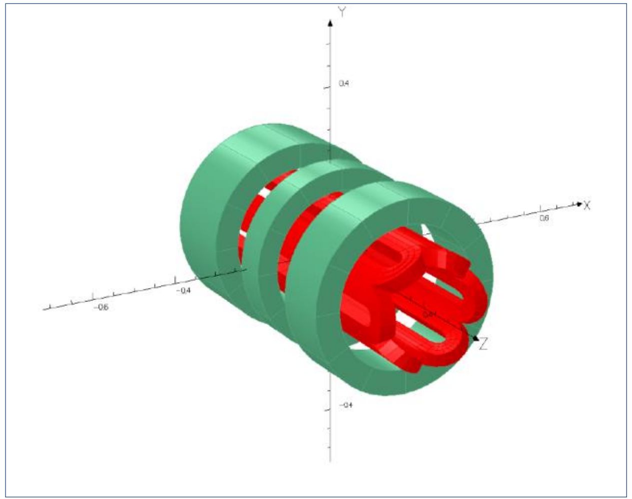
- Solenoidal field: 5.7 T – 1.2 T – 2.9 T
- Sextupole field: 3 T at 94 mm



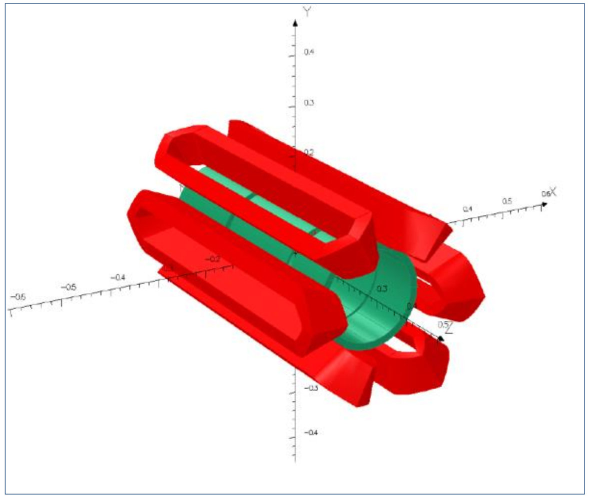


Different design options for ECR Ion Source magnets

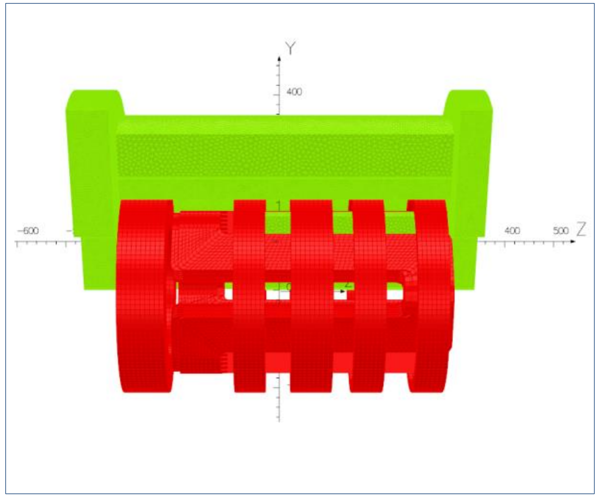
Sextupole in solenoid
VENUS/FRIB



Solenoid in sextupole
SECRAL



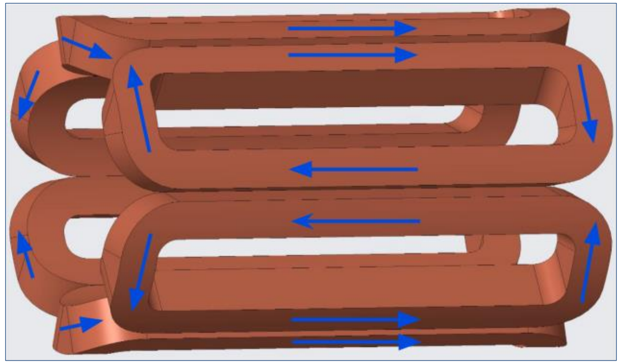
MARS



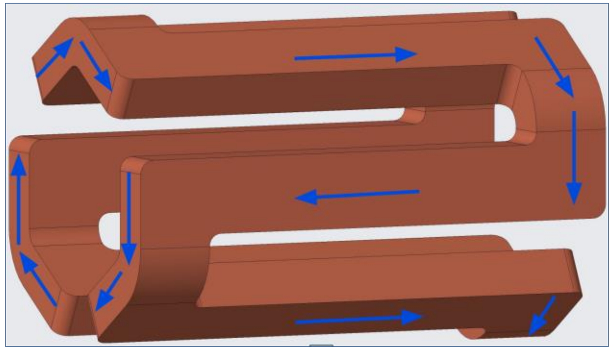
MARS cold mass design
Magnetic design

- MARS: Mixed Axial and Radial field System
  - Efficient magnetic design (sextupole ends contribute to the axial field) →
    - Possibility of reaching 45 GHz with Nb-Ti conductor
      - Similar load-line margin (10-15%) at 45 GHz as FRIB/VENUS configuration at 28 GHz
      - MARS would meet VENUS/FRIB performance with a very safe 40% margin
  - Electro-magnetic forces on the sextupole coil ends face outwards, both axially and radially
    - In VENUS/FRIB alternating end forces between coils
- Challenges: "Single" sextupole coil
  - Long fabrication process, "one-shot" type of condition

"Traditional" sextupole coils

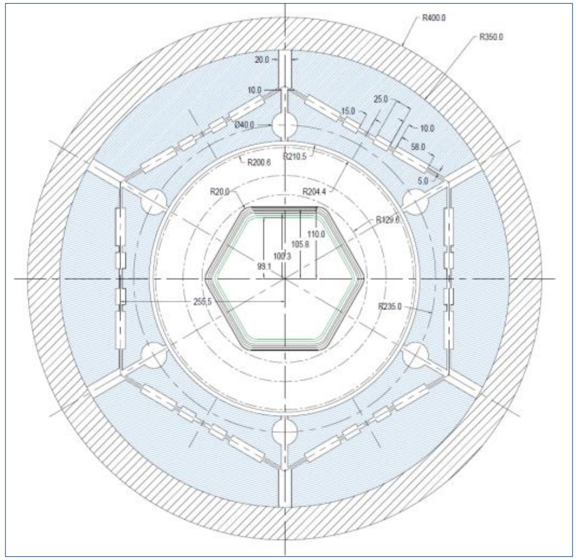


MARS sextupole coil

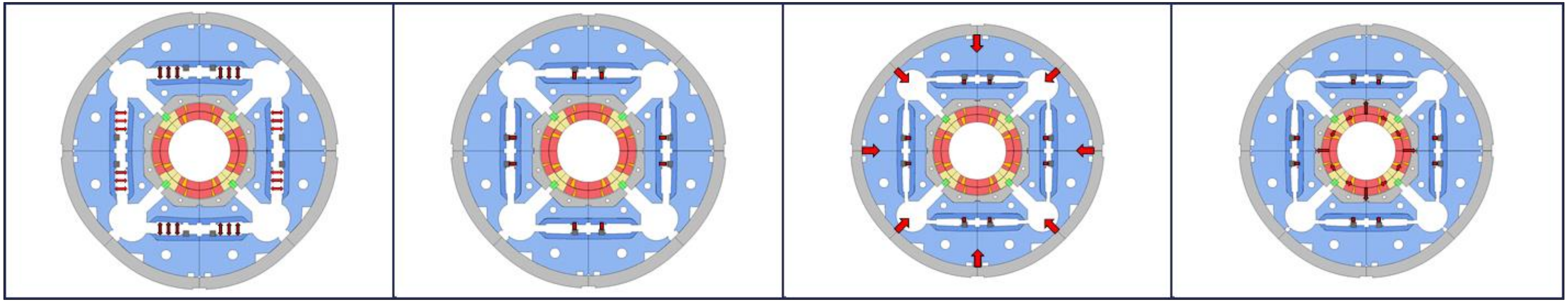


MARS cold mass design
Mechanical design

- Bladder and key support structure
  - Three main component surrounding the coils
    - Iron pad – iron yoke – aluminum shell
  - Room temperature pre-load provided with water-pressurized bladders
  - Additional pre-load provided during cool-down



Synergy with HEP - LHC luminosity upgrade MQXF quadrupole example



Outline

- Introduction: description and goals of the project
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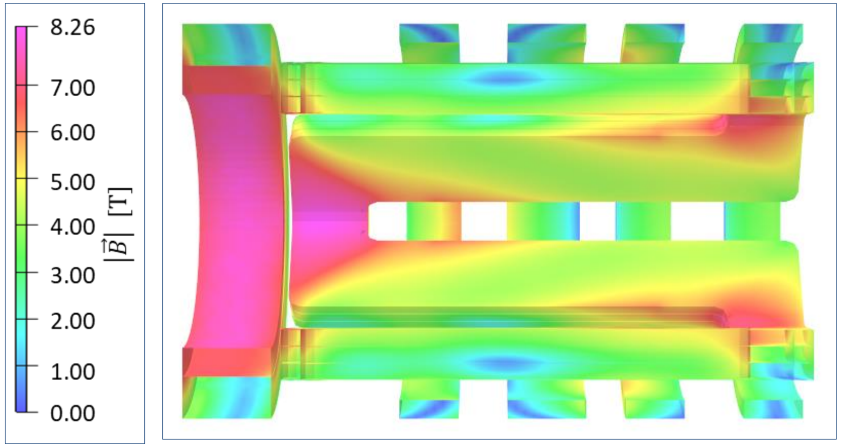
Project status: FY2023
Conceptual design and internal review

- Project started in October 2022

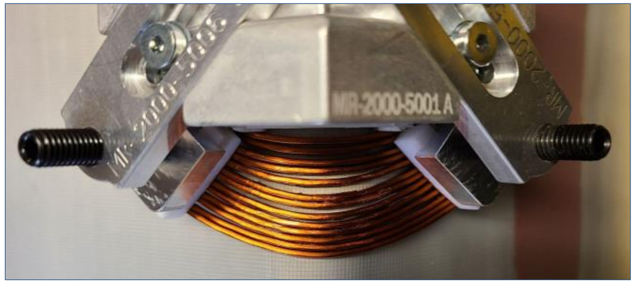
- Oct-Dec 2022
  - Review of previous work and conceptual design of the cold mass and tooling
    - Coil and structure design, magnetics, mechanics

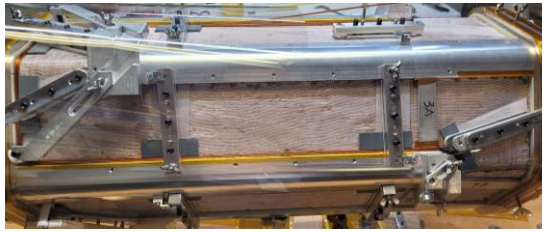
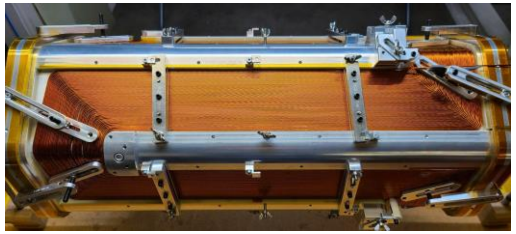
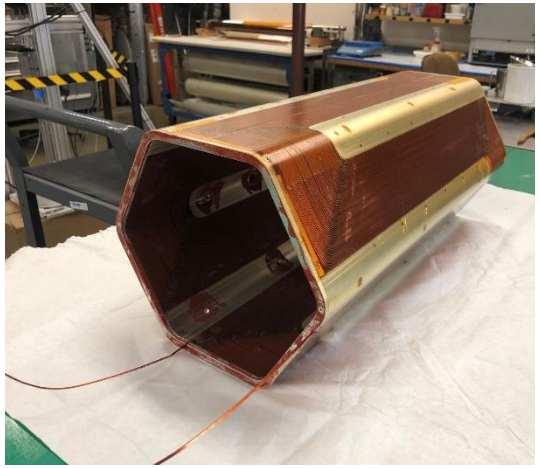


- Feb. 2023
  - Internal LBNL review of the cold mass design
  - Recommendations
    - *"Consideration should be given to performing additional test windings before launching the labor-intensive fabrication of the production coil."*
  - Decision to fabricate practice coil as risk mitigation strategy
    - Additional scope with respect to original plan

Project status: FY2023-FY2024
Tooling and practice sextupole coil

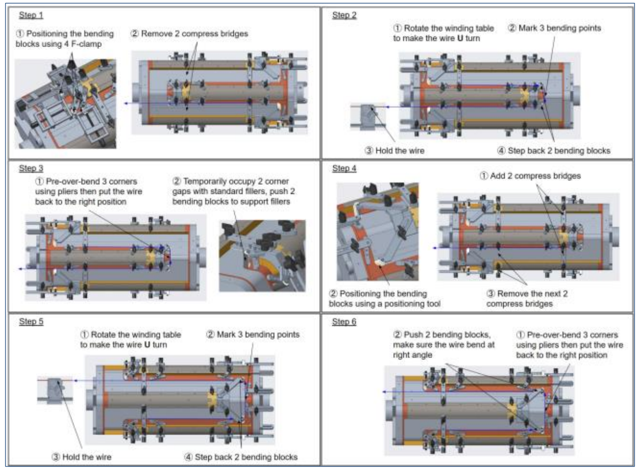
- Mar-Dec 2023
  - Tooling development
    - To guarantee correct positioning of sextupole turns
  - Winding and impregnation of the practice coil
  - Cut and inspection of the practice coil
    - Good turn positioning and impregnation
    - Extremely useful exercise to check tooling process, and quality of fabrication



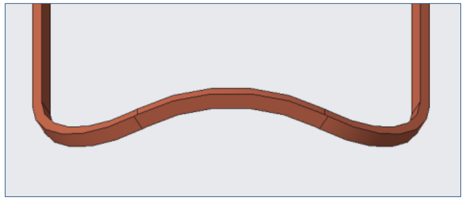

Project status: FY2024
Winding of sextupole coil

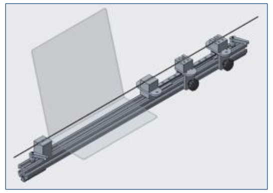
- Jan 2024
  - Start of the winding of the “real” sextupole coil
- Initial pace: about 1 layer per month
  - 24 to be done in total, each with 64 turns
- Training of progressively increasing number of technicians, now about 11
  - 2 h winding shifts, 2-3 times per week
- Definition and optimization winding procedures

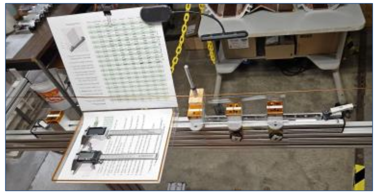


Project status: FY2024
Improvement of winding process

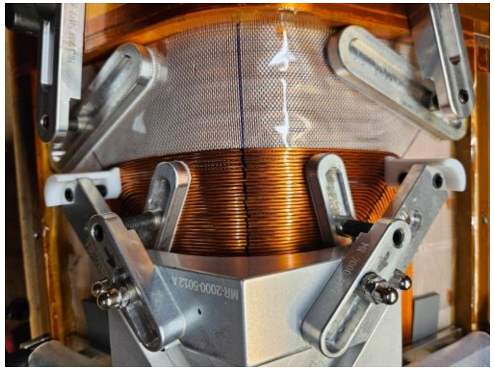
- Starting from October 2024, significant increase of pace (from 1 to 2 layers per month) and improvement of quality of winding
  - Developed a tool to pre-mark the bending positions





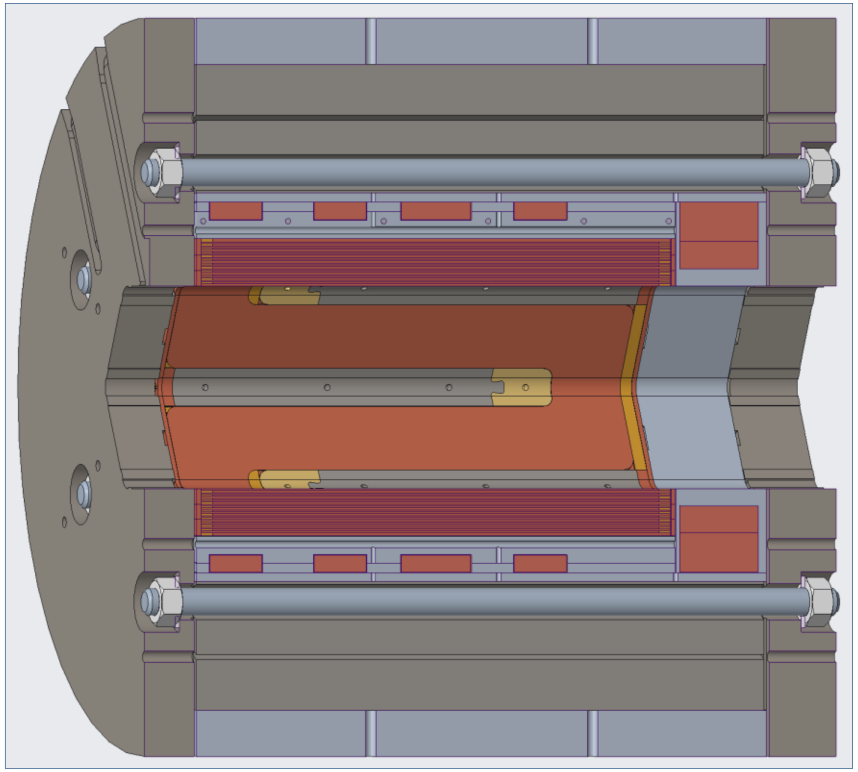


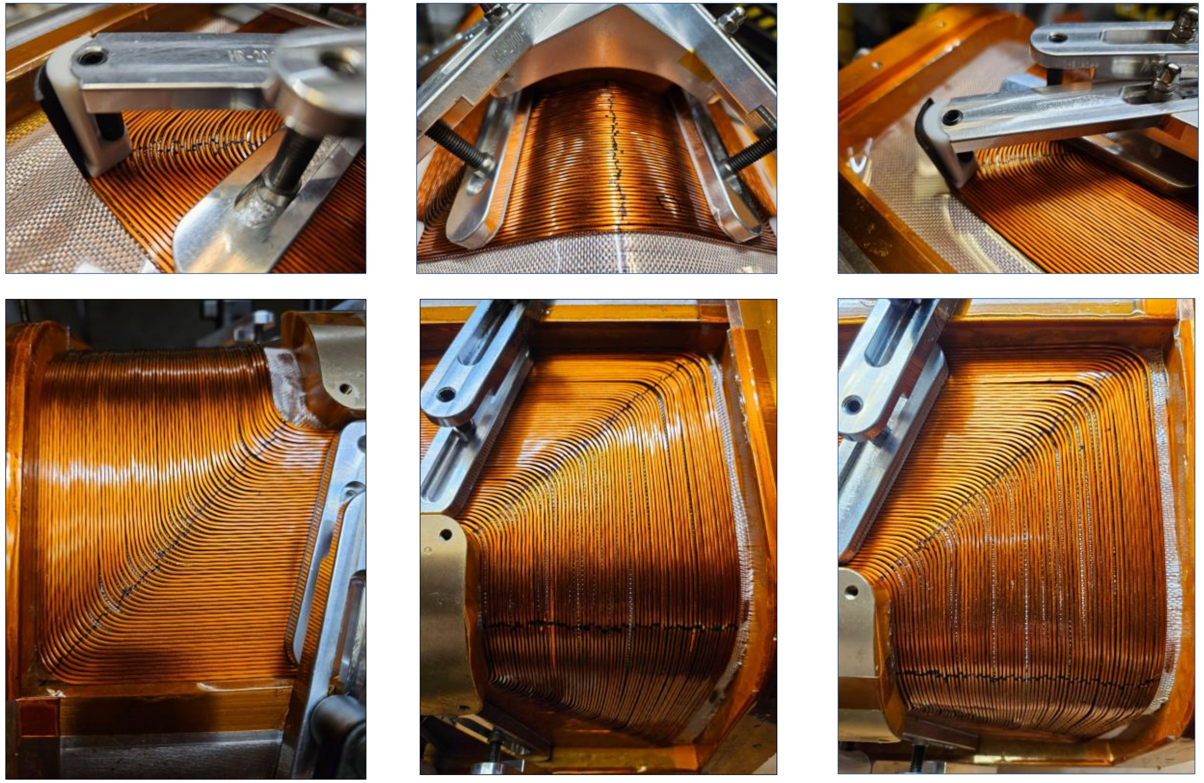
  - Faster and better positioning of the turns



Project status: FY2024
Winding in progress

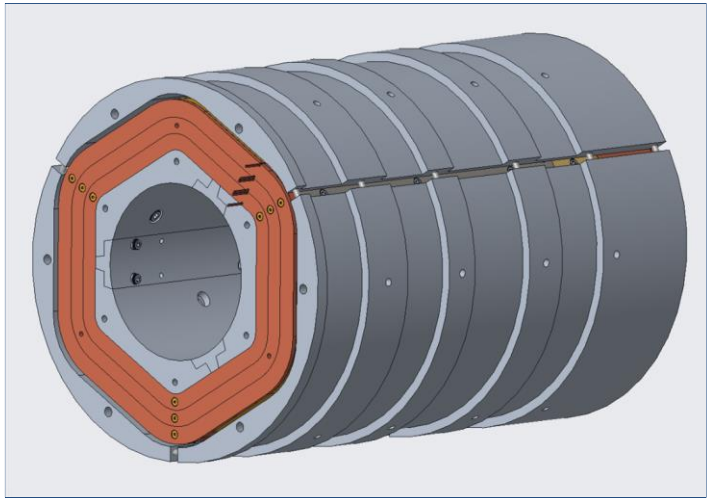
- Current status (November 2024)
  - 12 layers completed → half way

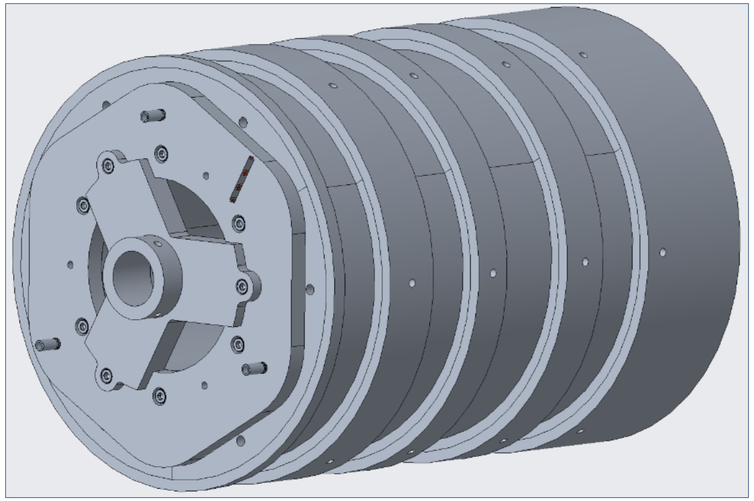


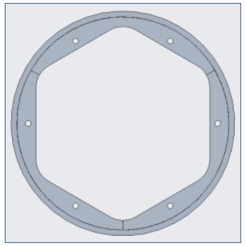


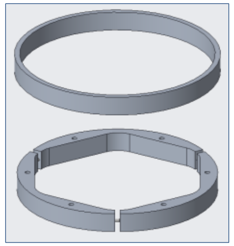
Project status: FY2024
New solenoid mandrel design

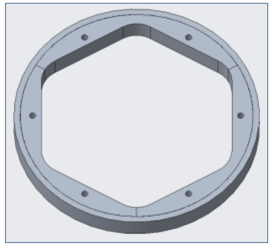
- Summer 2024: in order to ensure good contact between solenoid mandrel and sextupole coil, and ease mandrel machining
  - New solenoid mandrel design and new assembly procedure defined
    - Mandrel split in 3 parts, assembled around sextupole coils, and then impregnated
    - Shrink-fit with external rings successfully tested





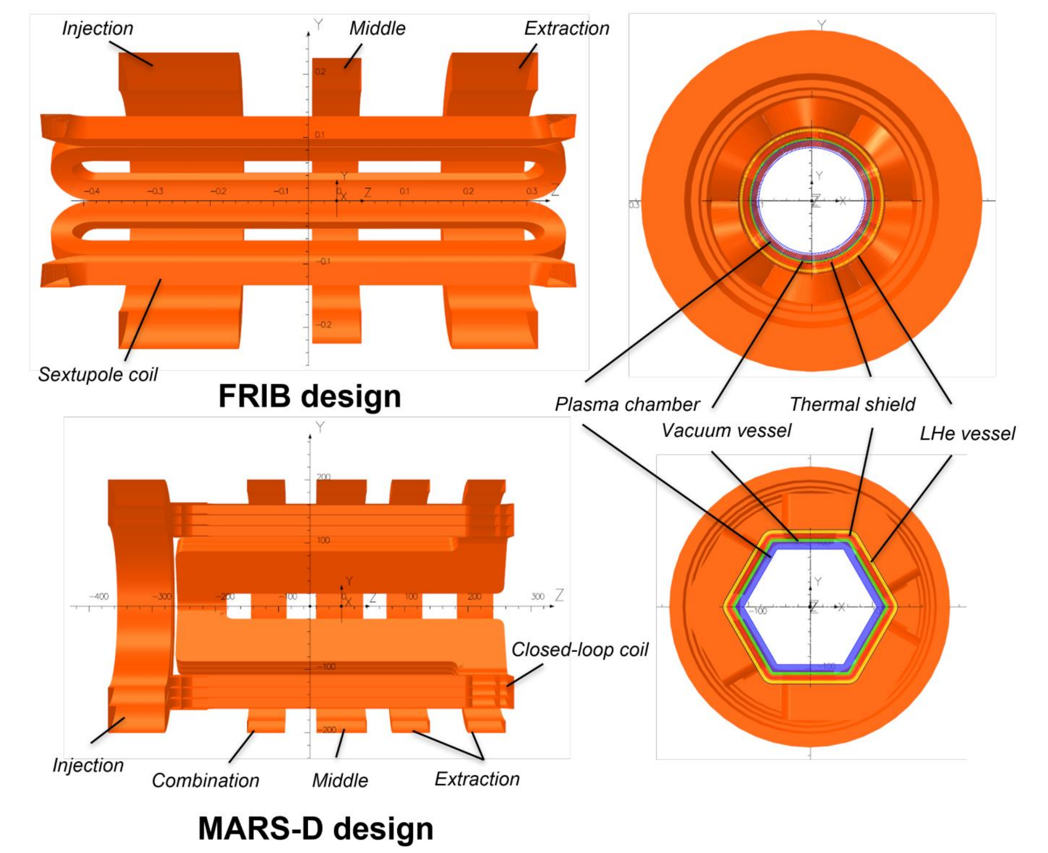






Project status: FY2024
Comparison analysis

- Presented at ASC 2024, and published on *IEEE trans. Appl. Supercond.*



SUMMARY OF THE DESIGN PARAMETERS OF THE ORIGINAL AND ALTERNATIVE MARS-D AND FRIB DESIGN CASES.

Item	Unit	*MARS-D*, 45 GHz			*MARS-D* design w. *FRIB* cond.			*FRIB*, 28 GHz			*FRIB* design w. *MARS-D* cond.		
Coil type	-	closed-loop	solenoid	total	closed-loop	solenoid	total	sextupole	solenoid	total	sextupole	solenoid	total
Conductor size	mm^2	1.45×0.71	1.91×1.23	-	1.65×0.96	1.90×1.00	-	1.65×0.96	1.90×1.00	-	1.45×0.71	1.91×1.23	-
Copper ratio	-	1.4	1.3	-	4.0	3.0	-	4.0	3.0	-	1.4	1.3	-
Coil volume	10^{-2} m^3	1.48	1.25	2.73	1.48	1.25	2.73	1.51	2.87	4.38	1.51	2.87	4.38
SC volume	10^{-3} m^3	7.98	6.74	14.7	5.30	3.26	8.56	5.33	7.46	12.8	8.27	15.9	24.2
Conductor length	km	5.6	10.9	16.5	6.4	6.9	13.3	6.6	16.0	22.6	5.6	24.5	30.1
Load line	%	88.6	83.8	-	87.1	86.0	-	87.2	77.6	-	85.3	78.0	-
MQE	μJ	10.4	5.0	-	6.2	4.8	-	6.1	9.4	-	11.1	6.8	-
Integral enthalpy	J/kg	0.43	0.65	-	0.29	0.26	-	0.29	0.49	-	0.51	0.81	-
$B_{inj}/B_{min}/B_{extr}$	T	5.7 / 1.2 / 2.9			5.2 / 1.1 / 2.6			3.9 / 0.6 / 2.0			4.4 / 0.7 / 2.2		
B_r	T	3.0 at 94 mm			2.7 at 94 mm			2.0 at 71.85 mm			2.2 at 71.85 mm		
ECR frequency	GHz	45			41			28			32		

- With respect to FRIB design, MARS design has
  - Higher frequency
  - Less usage of conductor
  - Less total coil volume

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Annual budget

	FY23	FY24	Total
Funds allocated	999	999	1998
Actual cost to date	668	827	1495

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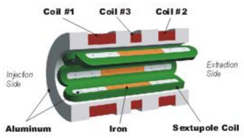
Project deliverables and schedule (within the allocated funds)

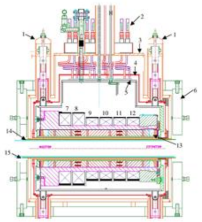
- Presented at 2023 NP Accelerator R&D PI Exchange Meeting
  - Completion of sextupole and solenoids coils by March 2025
- Updated schedule
  - Completion of winding of sextupole coil by August 2025
    - General comments
      - Very challenging and time-consuming winding on a new and innovative coil design, but now process optimized, procedures defined and team of about 11 technicians fully trained
      - New tooling, tested and validated, with significant increase of winding pace and quality
      - Excellent collaboration between LBNL NSD Divisions and ATAP Division teams, at all levels
        - » Conceptual design, analysis, fabrication….
- Additional funding (about 600 k$) awarded to complete cold-mass
  - Fabrication of solenoids and support structure, assembly, and test of the cold mass expected by summer 2026

Thank you

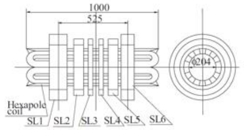
Appendix

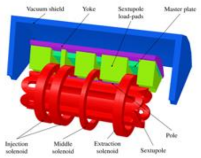
Superconducting ECR magnets (>20 GHz)



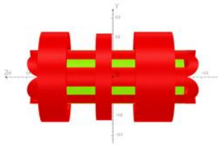


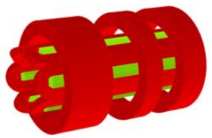
- 2001, M. Leitner *et al*, 28GHz NbTi, VENUS (*LBNL*)
    - 2005, P. Zavodszky *et al*, 24GHz NbTi, SuSi (*MSU*)



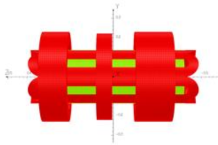


- 2010, T. Nakagawa *et al*, 28GHz NbTi, SC-ECRIS (*RIKEN-RIBF*)
    - 2018, G. Sabbi *et al*, **45GHz Nb_3Sn** (under development), FECR (*IMP, LBNL*)

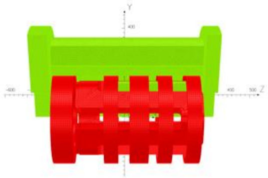




- 2019, D. Arbelaez *et al*, 28GHz NbTi, FRIB-I (*LBNL, FRIB*)
    - 2023, D. Simon *et al*, 28GHz NbTi (under development), ASTERICS (*CEA*)



- 2023, T. Shen *et al*, 28GHz Nb_3Sn (under development), FRIB-II (*FRIB, LBNL*)
    - 2018, L. Sun *et al*, 28GHz NbTi, SECRAL (*IMP*)



- 2016, M. Juchno *et al*, **45GHz NbTi** (under development), MARS-D (*LBNL*)

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Additional funding

- Sub-project 1
  - Completion of the MARS cold mass
- Sub-project 2
  - Design of the MARS cryostat components
- Sub-project 3
  - Development of Oven Technology for High Field Sources
- Sub-project 4
  - Beyond MARS, design of Nb3Sn ECR ion source towards 56 GHz

Tasks	Month	Cost (k$)
Task 1: Wind solenoid coils	1 - 3	$ 100
Task 2: Coil impregnation	4	$ 30
Task 3: Magnet assembly	5 - 7	$ 181
Task 4: Tests	8 - 10	$ 191
Oversight & Postdoc	1-10	$ 91
Total sub-project 2 Cost		**$ 593**

Tasks	Month	Cost (k$)
Task 1: Technical Requirements	1	$ 24.9
Task 2: Preliminary Design	2-10	$ 454.4
Task 3: Engineering & Final Design	11-21	$ 194.8
Oversight	1-21	$ 64.8
Total sub-project 2 Cost		**$ 738.9**

Task and Schedule	Month	Cost (k$)
Task 1: Design and build inductive oven with aiming barrels	1 - 6	$ 10.2
Task 2: Test new inductive oven in test stand, and then in VENUS	7 - 12	$ 35.4
Task 3: Construct rhenium inductive oven susceptor	13 - 18	$ 35.8
Task 4: Test uranium production in VENUS with rhenium susceptor	19 - 24	$ 10.9
Total sub-project 3 Cost		**$ 92.3**

Task and Schedule	Month	Cost (k$)
Task 1: Definition of technical specification and magnet parameters	1 - 3	$ 57.4
Task 2: 2D magnetic design and mechanical design	4 - 9	$ 132.3
Task 3: 3D magnetic design and mechanical design	10 - 15	$ 161.0
Task 4: Quench protection analysis	16 - 21	$ 158.0
Task 5: Documentation and reporting	22 - 24	$ 56.9
Total sub-project 4 Cost		**$ 565.6**